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the applications of satellites to Communications, Navigation and Surveillance for Aircraft Operating Over the Contiguous United States. Executive Summary

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TRW SYSTEMS GROUP

NASA · GODDARD SPACE FLIGHT CENTER · PREPARED UNDER CONTRACT NAS 5-21535 BY TRW NO. 14671-6009-R0-00 DEC. 1970

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TRW NO. 14671-6009-R0-00

the applications of satellites to

COMMUNICATIONS, NAVIGATION AND SURVEILLANCE

For Aircraft Operating Over the Contiguous United States

EXECUTIVE SUMMARY

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MALLINCKRODT, MORRISON, ZIPPER, ET AL

DECEMBER 1970

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER

Prepared Under Contract NAS 5-21535 by

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ACKNOWLEDGEMENT

This study has been an extensive team effort. Numerous technical personnel have made contributions to this report. A number of individuals who made very significant contributions to the study are mentioned in the appropriate volume. In addition, valuable technical information was obtained during this study through discussions with the National Aeronautics and Space Administration, the Department of Transportation, the Federal Aviation Administration, the National Transportation Safety Board, the Air Transport Association, Aeronautical Radio Incorporated, the MITRE Corporation, Aerospace Corporation, North American Rockwell Corporation, the Aircraft Owners and Pilots Association, the Airline Pilots Association, and a number of U. S. air carriers. In addition, we gratefully acknowledge the significant contribution made by NARCO, King Radio, Bendix Avionics, Collins Radio, and Wilcox to the LIT pricing effort. Finally, a special acknowledgement is given for the assistance provided by the DOT/Transportation Systems Center who, as the NASA Electronics Research Center, initiated this study and to those individuals at Goddard Space Flight Center who assumed responsibility for and an interest in this study.

ABSTRACT

This report describes the results of a study which has been performed for the National Aeronautics and Space Administration. The objective of this study has been to determine on a priority basis the satellite applications to communications, navigation, and surveillance requirements for aircraft operating beyond 1975 over the contiguous United States and adjacent oceanic transition regions, and to determine if and how satellite technology can meet these requirements in a reliable, efficient, and economical manner.

Major results and conclusions of the study are as follows:

- The satellite applications of greatest importance are surveillance and rapid collision warning communications.
- The necessary technology is now available as demonstrated by an attractive system concept based on this technology.

In the satellite-based air traffic control concept all aircraft making use of the system will have a Location/Identification Transmitter (LIT) and antenna for surveillance which is unique to the satellite system. This low-cost transmitter permits identification and accurate three-dimensional location of all airborne aircraft approximately every second. Most of these aircraft will also be equipped with LIT backlink receivers providing short access time mid-air collision warning. In addition, aircraft will have an option of satellite navigation equipment for on-board determination of highly accurate three-dimensional position and velocity information. The use of satellites for rapid and reliable data communication from any place in the country to an aircraft anywhere over the country is also possible.

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1. THE PROBLEM AND A SOLUTION

"Air traffic is in crisis. The crisis now manifest at a few high density hubs is the direct result of the failure of airports and air traffic control capacity to keep up with the growth of the aviation industry ... Unless strong measures are taken, forces presently in motion will blight the growth of American aviation." This quotation from the report of the Department of Transportation Air Traffic Control Advisory Committee (Alexander Committee) also might well have come from the final report of the Curtis Committee in 1957 (Ref. 2) or from the report of the Hough Committee (Project Beacon) in 1961 (Ref. 3). Clearly, it has been extremely difficult to provide an ever-expanding high quality air traffic control service to the extremely dynamic and rapidly expanding aviation community.

Requirements

The airspace system today reflects the evolutionary development of ground facilities to exploit the greatest potential of air travel in keeping with increasing user demands and advances in aircraft performance. Since the practical application of the nation's growth in technological skill has not been able to keep up with the demand, there has been an increasing reliance on new strategies to accommodate the air traffic. Examples of these strategies are the quota system and recently-instituted terminal control areas in major air terminals.

Within the broad definition of the national airspace system, all airspace over the United States is regulated in one way or another. Different controls are specified for different portions of the airspace, varying from direct, real-time vector commands from ground controllers to simple right-of-way procedures promulgated through federal aviation regulations. There are three basic categories of airspace now defined by the FAA, uncontrolled airspace, controlled airspace (also called mixed airspace), and positive control airspace. In uncontrolled airspace, VFR and IFR flights operate without ATC approval or control. The control is simply procedural; no separation service is provided by ATC. In controlled airspace, all flights operating under IFR are subject to prior approval and direct control of ATC. VRF flights may operate in the same airspace without such approval or control but must adhere to the applicable procedures for this area. In positive control airspace <u>all</u> flights must operate under instrument flight rules and are subject to prior clearance and real-time control, regardless of weather and visibility.

Significant air traffic projections are shown in Table 1. Aircraft fleet size is important because it indicates the size of the market and points out that the vast majority of aviation fleet is, and will continue to be, general aviation. The total number of annual flights is of interest for two reasons: first, about two-thirds of all flights are itinerant; second, the number of IFR flights will increase from less than a third of the current itinerant flights to over half of a much larger number of future flights. Thus the air traffic control system load (which is related primarily to controlled or instrument operations) will grow disproportionately faster than the increase in aircraft population. The peak instantaneous airborne aircraft count shows that a control system operational in 1980, with a 30-year design life, should be capable of handling about 100, 000 airplanes at one time, although the capability of handling this many aircraft need not be built into the system at the outset. Finally, of the 54, 400 aircraft airborne at the peak instant in 1995, 42, 400 will be on itinerant flights, but over 10, 000 of those will either have not yet departed the terminal area or will have already arrived at their destination terminal area. Thus, over 40 percent of the traffic will be in terminal areas, which are the areas of greatest likelihood of mid-air collisions.

Further studies of the existing and imminent requirements facing an air traffic control system show the following:

- The growth in transportation requirements to what are now thinly populated areas (e.g., popular vacation resorts) may cause broad area coverage requirements to accelerate even faster than expected.

- Normal maneuvers prevail for such a high percentage of flight time that the control system should be designed to handle normal maneuvers, i.e., unusual flight conditions such as aerobatics should not set system constraints.

- The "see and be seen" approach to collision avoidance is inadequate.

Table 1. Aviation Traffic Projections (Adapted from Ref. 4)

	TYPICAL LIFETIME OF A MAJOR AIR TRAFFIC CONTROL SYSTEM CONCEPT			
	1968	1980	1995	2010 (Extrapolation)
Aircraft Fleet Size				
Air Carrier	2,500	3,500	6,500	13,000
General Aviation	114,000	214,000	500,000	~1,000,000
Military	20,000	20,000	20,000	20,000
All Users	136,500	237,500	526,500	~1,000,000
Annual Flights (In Millions)				
Itinerant	23.6 (29% IFR)	46.4 (43% IFR)	109.5 (49% IFR)	200 (>55% IFR)
Local	12.1	20.7	47.9	100
Total	35.7	66.6	157.4	~300
Peak Airborne Aircraft				
Air Carrier	1,300	2,100	4,600	9,000
General	8,000	16,800	46,300	84,000
Military	3,500	3,300	3,500	7,000
All Users	12,800	22,200	54,400	~100,000
Itinerant			42,400 (~31,800 En route)	
Local			12,000 (~22,600 Terminal)	

- A high-quality surveillance system is required in terminal areas and for those en route situations in which high traffic density makes it desirable to organize traffic into narrow parallel tracks.

- An examination of the CNS implications of the two major 1967 mid-air collision disasters indicated the need for full service CNS coverage over wide areas and the urgent need for a solution to the mixed airspace problem.

- If the concept of mixed airspace is to survive, of course, a scheme such as the short access time collision warning (or the so-called intermittent positive control scheme) must be implemented.

The total air traffic control problem is, of course, extremely complex, but sufficient confidence in the requirements analysis has been established to draw up guidelines on which to evaluate the feasibility of any proposed improvement in air traffic control capability.

Satellite CNS System

In this framework, it is clear that satellites offer the potential for significant improvement in air traffic control capability. The use of satellites for aircraft communications, navigation, and surveillance, nevertheless, must be justified on the basis of reduced costs, improved reliability, accuracy, availability, and coverage with respect to alternative systems and procedures. Accordingly, NASA's objective has been to determine on a priority basis the communications, navigation, and surveillance requirements for aircraft operating over the contiguous United States (including oceanic transition regions) in 1975 and beyond, and to determine if and how satellite technology can meet these requirements in a reliable, efficient, and economical manner.

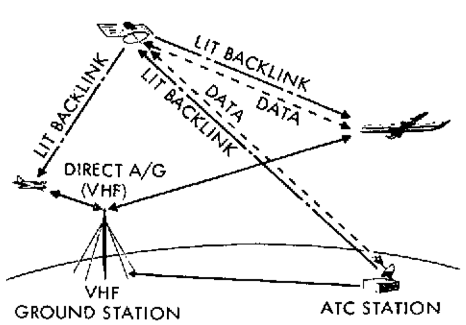
The system that meets these objectives consists of a four-satellite constellation (with two spares), user aircraft, and ATC ground centers. The satellites operate in 24-hour orbits with continuous coverage of the continental United States and provide communication, navigation, and surveillance services for ATC. Highlights of the system concept and reference data are shown in Figure 1 which is also reproduced on the inside back cover of this report.

For surveillance, each aircraft in the system transmits autonomous coded-pulse bursts which are relayed by the satellites to the ground centers. The centers identify the aircraft from their codes and locate their position in three-dimensional space by multilateration with respect to the satellites. This concept is discussed in more detail in Section 2.

All aircraft will be equipped with a small lightweight antenna and transmitter operating through the satellite network. This system will be characterized by the following:

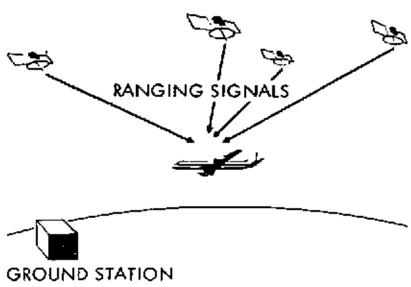
- The location of all airborne aircraft precisely known in three dimensions (50 to 300 feet) with updating about once per second
- Identification of all airborne aircraft
- Uniform coverage over the entire United States
- Feasibility of maintaining system saturation point well above projected traffic forecasts for this century with a relatively modest use of RF spectrum
- Low-cost avionics.

COMMUNICATIONS



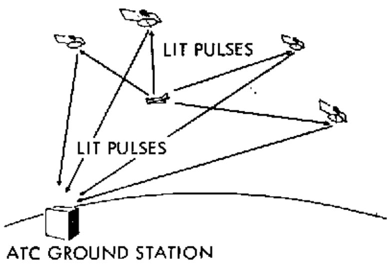
PARAMETER	DATA	LIT BACKLINK
CHANNELS	2/SAT.	2
CAPACITY/CH	1200 BPS FULL DUPLEX	100 MESSAGES/ SEC
CARRIER FREQ	5140-5170 MHz (Gnd) 950-980 MHz (A/C)	5050 MHz UP 940 MHz DOWN
BANDWIDTH	100 KHz/SAT	500 KHz

NAVIGATION



PARAMETER	NAVSTAR
CHANNELS	1
CAPACITY	UNLIMITED
CARRIER FREQ	1550 MHz
BANDWIDTH	2 MHz

SURVEILLANCE



PARAMETER	LIT
CHANNELS	2
CAPACITY/CH	50,000 UPDATES/ SEC
CARRIER FREQ	912.5 MHz UP 5087.5 MHz DOWN
BANDWIDTH	50 MHz

NOTE: SAME SATELLITES FOR ALL THREE FUNCTIONS. CARRIER FREQUENCIES ARE TENTATIVE AND APPROXIMATE.

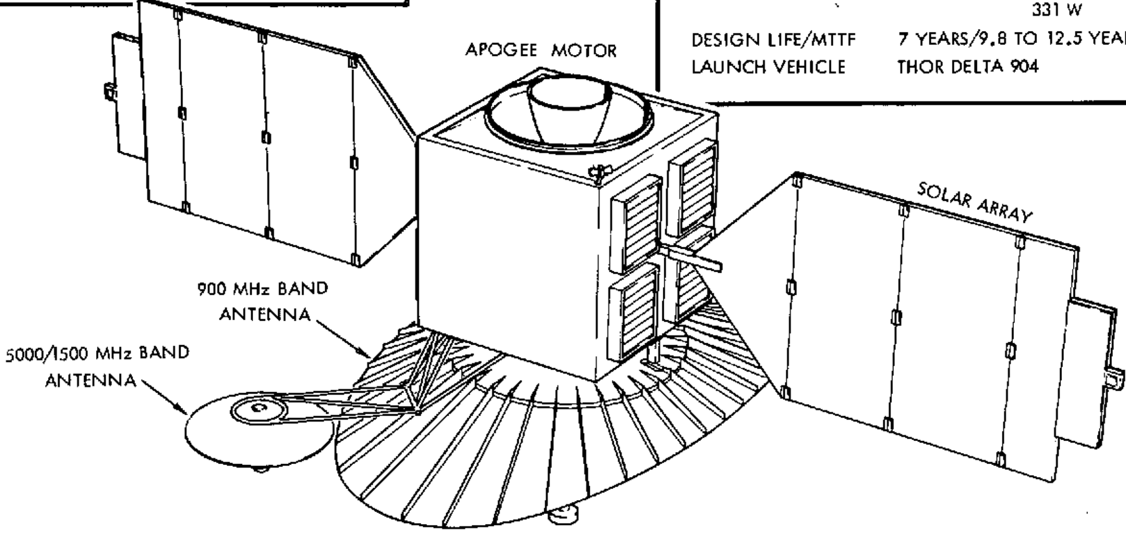
SYSTEM DATA

6-SATELLITE 16° X-CONFIGURATION
~200 FT ACCURACY (1σ ALT, HORIZONTAL CEP)
PROBABILITY OF OUTAGE, 30 YR LIFE ≅ 3.3%

SATELLITE DATA

PAYLOAD 2 LIT	100 W	20 LB
2 LIT BACKLINK	46 W	20 LB
1 NAVSTAR	25 W	25 LB
2 DATA LINK	60 W	20 LB
OTHER SATELLITE FUNCTIONS	100 W	637 (1146) LB
	331 W	722 (1231) LB

DESIGN LIFE/MTTF 7 YEARS/9.8 TO 12.5 YEARS
LAUNCH VEHICLE THOR DELTA 904



LIT SYSTEM CAPACITY

ATCAC AIRCRAFT POPULATION FORECAST
1995 - 54,000 PEAK AIRBORNE
525,000 REGISTERED

LIT CHANNEL CAPACITY (25 MHz BAND)
50,000 AIRCRAFT POSITION UPDATES/SEC
500,000 AIRCRAFT ID'S ASSIGNABLE *

* FROM PRODUCT OF 31,255 PRP'S AND 16 BIPHASE CODES

LIT MODULATION PARAMETERS

TRANSMITTED PULSE WIDTH	51.1 μSEC
PULSE REPETITION PERIOD (PRP)	BETWEEN 1.0 AND 1.31 SEC/PULSE
NUMBER OF DISCRETE PRP'S	31,255 - SPACED 10 μSEC APART
BIPHASE CODE LENGTH	511 BITS
BIT LENGTH	0.1 μSEC (COMPRESSED PULSE WIDTH)
NUMBER OF BIPHASE CODES	16

Figure 1. Satellite CNS System-Reference Data.
LIT = location-identification transmitter

In contrast, the current radar system by itself yields no altitude information and has much larger position errors. With the applicable national standard (Ref. 6) specifying an accuracy of ±1000 feet and ±1.0 degree at the display, radar-system measurements to date (Ref. 7) under idealized conditions show an accuracy of ±380 feet in range and 0.1 to 0.25 degree in azimuth, amounting to position errors of approximately 900 and 1600 feet at 30 and 150 nautical miles respectively. Improved accuracy, higher data rates, and identity and altitude reporting are all considered feasible, but impose the expense of new interrogators with electronic scanning devices. Further, uniformity in altitude determination will remain difficult and radar's line of sight limitation makes it impractical to obtain uniform coverage over large volumes of airspace. Finally, the current total number of air traffic control radars in use is about 204, resulting in high replacement, maintenance, and operations costs.

For navigation, the satellites emit ranging signals. Using different signals from the same satellites, aircraft can navigate with considerable accuracy in three dimensions. Only larger aircraft are likely to use this service because of the cost of the airborne navigation equipment. This technique is discussed in Section 3.

The satellites are also equipped to provide communication links between aircraft and ground centers. Two types of links have been studied in this connection. The first is a simple low-data-rate collision warning link from ATC ground centers to aircraft which works in conjunction with the surveillance system. The second is a two-way 1200 bits/sec data link which only large commercial or military aircraft are likely to use. Both communication links are treated in Section 4.

The Satellite

The conceptual design of the satellite, described first in Ref. 5, and illustrated in Figure 2 provides sufficient power to accommodate two location-identification channels, two backlink (collision warning) channels, two 1200 bits/sec data channels and a navigation channel. This satellite weighs about 1225 pounds (Table 2) and can be launched on a

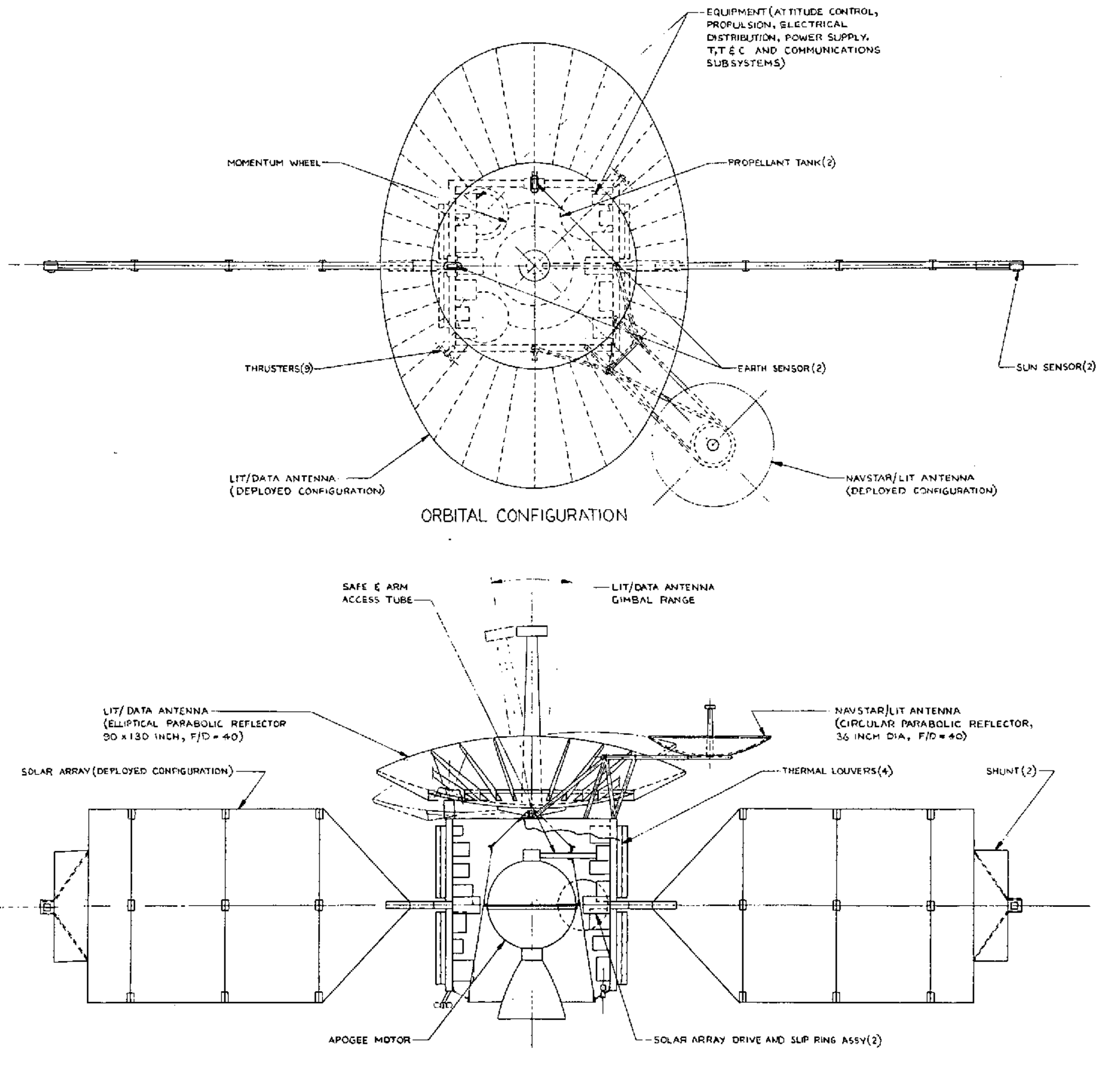


Figure 2. Satellite Configuration

Thor Delta 904, which includes nine solid-strap-on rockets on the first stage, an inertially guided second stage, the TE 364-4 third stage, and a bulbous fairing. This combination can place 1250 pounds into a transfer orbit to synchronous altitude at an inclination of 23 degrees. The 23-degree inclined transfer orbit is selected because of range safety restrictions on the reentry of the second stage. At apogee to the transfer orbit the injection motor on the satellite adjusts the inclination to the selected value and circularizes the orbit.

Table 2. Satellite Weight Breakdown

Satellite Breakdown	Pounds
Electrical power	167
Electrical distribution	45
Telemetry, tracking, and command	24
Surveillance, navigation, communication equipment	90
Hydrazine fuel	68
Apogee motor	559
Antennas	62
Attitude control	75
Structure	99
Thermal control	32
Balance weight provision	4
Total	1225

The antenna is designed to cover the continental United States with an elliptical beam of 9.4 x 6.5 degrees (at 900 MHz). The antenna is an unfurlable, elliptical paraboloid dish gimballed in one axis. The other communication links are handled by a single fixed circular parabola 3 feet in diameter. This antenna carries both the navigation link to the aircraft at 1.6 gHz (approximately earth coverage) and all communications between the spacecraft and the ground at 5.2 gHz.

Primary electrical power for the satellite is furnished by two solar array paddles which rotate about one axis. The batteries are sized for full eclipse capability (70 minutes) with two batteries. If one battery fails, approximately 60 percent eclipse capability remains. The electrical power requirements are listed in Table 3.

Table 3. Electrical Power

Equipment	Power (watts)
Communication	
LIT	100
NAVSTAR	25
LIT backlink	46
Data link (two 1200 bit/sec channels)	60
Converter	25
Telemetry and command	22
Attitude control	32
Electrical distribution	5
Power control unit	3
Battery trickle charge	12
Total	331

Ground Stations

The launch and injection functions can be supported by the STADAN range facilities, without any change required of the existing facilities. The rest of the ground system (see Figure 3) consists of the following five segments:

1) Four Location-identification Data Processing Centers (LDPC)

2) 20 Air Route Traffic Control Centers (ARTCC)*

*The FAA plans to deactivate one of the 21 existing centers.

3) One Satellite Command and Control (C and C) Station

4) Ground Communications Network (GCN)

5) LIT Calibration Beacon Network.

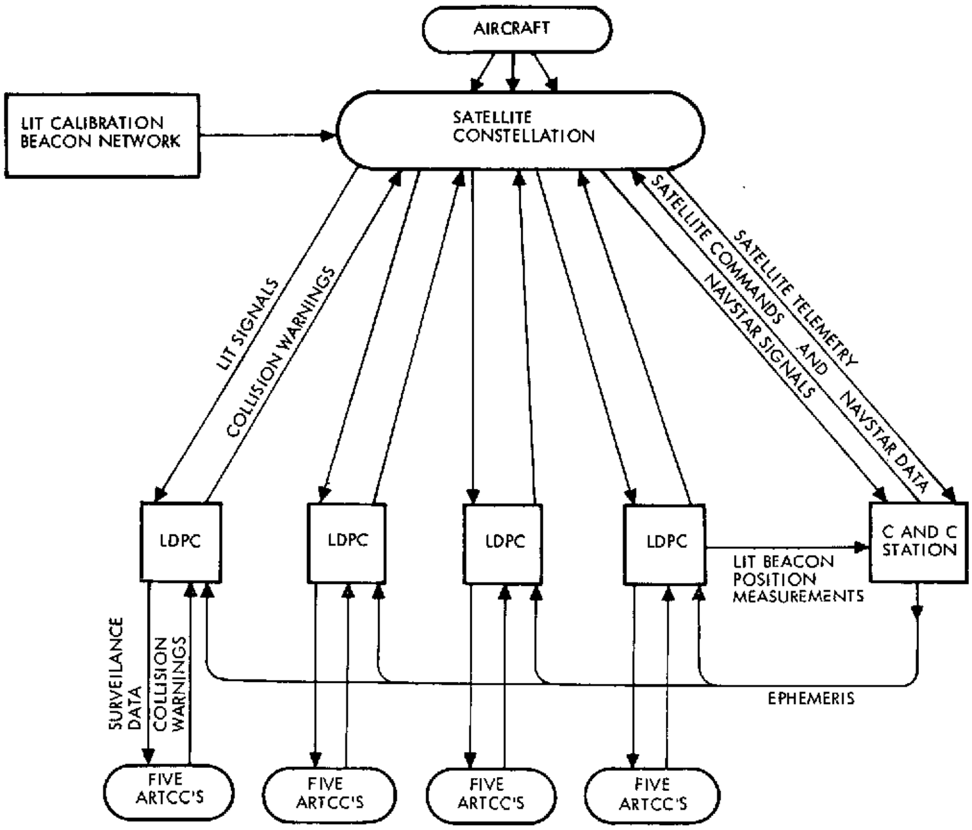


Figure 3. CNS Satellite Ground System

Of these, Segment 2, the ARTCC's, wherein ATC operations will be conducted, is the only one that is not peculiar to this satellite system. The LDPC's provide surveillance data to the ARTCC's and transmit backlink messages to aircraft under command from the ARTCC. Each LDPC covers the aircraft in approximately one-fourth of the airspace and is responsible to the five ARTCC's in its area of coverage. While surveillance data is available at each LDPC for all aircraft, only aircraft in its area are of concern to a LDPC. All four LDPC's are identical and each receives LIT signals from all six satellites including signals from the calibration beacon network. Specifically, the functions of these stations are:

- Identify and track aircraft by processing signals received from satellite network
- Disseminate surveillance data to appropriate ARTCC's
- Transmit collision warning messages via satellites to aircraft
- Provide any satellite communication links with aircraft.

The C and C station provides master control for the six operational satellites. It follows the concept of a conventional satellite telemetry and command ground station, and is conveniently divided into the following:

- Two sets of transmitter-receiver equipment with antennas, receivers, transmitters, telemetry decommutators, and command encoders
- A telemetry and command data-processing computer (with backup) together with displays, line printers, and tape punches
- A set of NAVSTAR receiving and data processing equipment (with backup)
- A tracking data computer with backup
- A communications terminal.

The C and C station operates at S band for compatibility with the STADAN network. It monitors the health of all six satellites on a roll-call basis. These data are processed and disseminated to the controlling agency and ARTCC's. Via its command uplink, the C and C station controls the satellites. Another function of this station is to receive NAVSTAR signals from the satellites and compute oscillator error from a knowledge of ephemeris and station geography. The command link is used to insert data representing oscillator error and ephemeris into the NAVSTAR memory on the satellites. Finally, this station acts as the master for all four LDPC's and performs all satellite ephemeris computation.

The calibration beacon network consists of a number (perhaps 50) of unmanned beacons at known (surveyed) sites such as airports or VOR's. The beacons put out signals identical to the aircraft LIT transmissions and are assigned a permanent block of LIT codes. The purpose of this calibration network is twofold:

- Provide a network of tracking sites for computing satellite ephemerides
- Permit real-time calibration of the ionospheric errors in the vicinity of each beacon.

2. AIRCRAFT SURVEILLANCE

To minimize the user avionics price, the aircraft's role in the surveillance scheme is limited to the autonomous transmission of a ranging signal. As indicated in Figure 4, each satellite in the network relays the signals that it receives from aircraft to a ground station.

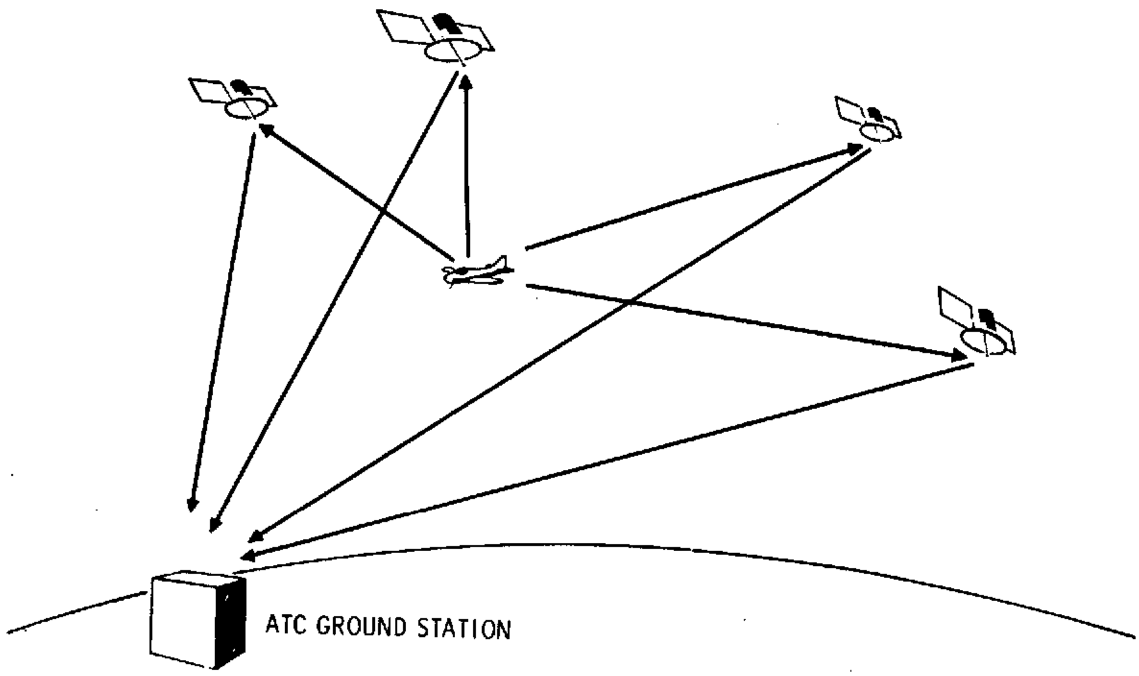


Figure 4. Satellite Surveillance System

The times of arrival from each satellite are treated as straight range measurements. Thus, four unknown quantities must be computed, the three components of position and the time of aircraft transmission. With four satellites, equations for these computations are straightforward. The equations and the computational procedure are described in Ref. 8. Inherent in the computation is the calibration of the aircraft's oscillator or clock so that the ground station knows the aircraft transmission epoch within less than a microsecond.

The Signal

The transmitted aircraft signals consist of 51.1-microsecond bursts which are biphase-modulated by a 511-bit code. Each aircraft is assigned a unique combination of code and pulse repetition period (PRP) which together are used to uniquely identify an aircraft. Some 31,255 PRP's are assigned in 10-microsecond increments between 1.0 and about 1.3 seconds. The capacity of a surveillance channel is 50,000 pulses/sec or somewhat over 50,000 aircraft. In addition, there are 16 different biphase codes so that a total of slightly over 500,000 assignable aircraft identifications (ID's) are available on each surveillance channel.

As shown in Table 1, by 2010 a million registered aircraft in the United States are anticipated with a peak traffic of 100,000 aircraft airborne. Therefore, two location-identification channels would be required to have enough ID's available for individual assignment to all aircraft and to handle peak traffic. Each channel occupies 20 MHz of RF bandwidth so that, with 5 MHz guard bands, a total of 50 MHz is required.

The code and pulse repetition period of all arriving pulses are identified at the ground station by a bank of matched code filters in the receiver which compress the 51.1-microsecond pulses to 0.1 microsecond and divide them into 16 separate groups (one for each biphase code). Pulse sorting computers then identify PRP's.

In the track mode, a computer predicts the time of arrival of subsequent pulses based on the known PRP's; if pulses from each satellite arrive at the proper times (within a tolerance band), the track is maintained. If pulses are not detected at the proper times, the track is still maintained for three frames. If no pulses are detected during these three frames, the PRP track is dropped and the ATC system is notified. Subsequent pulses would cause the aircraft to show up as a "new target".

The PRP sorting process converges to a solution quite rapidly. For instance, if 1000 unidentified pulses existed at one time frame, on the average only two or three frames (pulse periods) would be required for successful identification of all the pulses. However, because computer storage requirements become excessive, all pulses would not be identified in parallel but in small groups of 100 pulses. The first 100 pulses can be identified, on the average, in about 2.5 seconds. The process accelerates as pulses are identified and the entire 1000 can be identified in less than 25 seconds.

Finally, a position computer calculates the location of all tracked aircraft from the times of arrival of the identified pulses from each satellite and stores this information. Updating occurs as often as the ATC system desires but is limited to multiples of the PRP.

In designing the pulse modulation the goal is to provide the capacity to locate and identify up to 100,000 aircraft per second using the same signal space. Therefore, the modulation should contain a potential signal processing gain on the order of 60 to 70 db. The signal processing gain is provided by a combination of low duty cycle transmissions (pulses) and pulse compression at the ground receiver. The modulation parameters are shown in Table 4. The compressed pulsewidth of 0.1 microsecond results not only from the processing gain requirement but also from an accuracy requirement on pulse arrival time measurements for position location.

Table 4. Signal Modulation Parameters

Transmitted pulsewidth	51.1 microseconds
Pulse repetition period	Between 1.0 and 1.3 sec/pulse
Number of discrete PRP's	31,255 spaced 10 microsec apart
Biphase code length	511 bits
Bit length	0.1 microsec (compressed pulsewidth)
Number of biphase codes	16

The 10-microsecond PRP spacing is chosen so that a combination of doppler shift and transmitter oscillator error will not cause overlapping of adjacent PRP assignments. At less than Mach 1, doppler shift (including satellite motion) will not exceed 1.5 parts per million. The transmitter oscillator long-term stability will be one to two parts per million (achievable at low cost) so that the maximum PRP jitter is ±3.5 microseconds. For high performance aircraft, better oscillator stability can be provided to offset the increased doppler.

The probability of a particular pulse being interfered with during a particular period is 3×10^{-3} if pulses from all aircraft are assumed to be uniformly distributed over the pulse period. Thus the probability of obtaining at least four measurements from four satellites for a three-dimensional position fix during any period is $(0.997)^4$ or 0.988; only 12 position fixes out of 1000 would be lost and they will be randomly distributed. With the fix rate capability of once per second, this is quite acceptable.

Aircraft Transmitter

The aircraft location-identification transmitter is small, lightweight, and inexpensive. Although it could be designed to be turned on by a pilot switch, it more likely would be activated by a switch tied into the ignition system. The operation of the transmitter can be quickly and easily verified at an airport before takeoff.

Six different designs have been investigated for the transmitter, covering three carrier frequencies and two pulsewidths at each frequency. Table 5 lists the six designs.

The transmitter oscillator is the timing source for the digital logic which derives the biphase code and pulse repetition period. The oscillator also feeds a multiplier-amplifier-modulator chain which drives the final power amplifier stage. Therefore, the accuracies of the pulse repetition period, pulse code rate, and carrier frequency are established by the oscillator accuracy. The oscillator will probably have to be recalibrated once a year to stay within 2 ppm accuracy. This could be done as part of the annual relicensing of aircraft.

Table 5. Transmitter Designs

Design	Frequency (MHz)	Pulse Length (microsec)	Peak Power (watts)
A	1600	51	2500
B	1600	204	700
C	900	51	890
D	900	204	240
E	450	51	350
F	450	204	90

The A design is shown in Figure 5. In the B design, pulse amplifier 4 is removed because of the lower power output. Design C is identical to B except that the x5 multiplier is replaced by a x3 multiplier because of the lower frequency output. Design D is identical to C except that pulse amplifier 3 is removed because of the lower power output. For designs E and F, the last x3 multiplier is removed and solid-state amplifiers are used for the final output power stage.

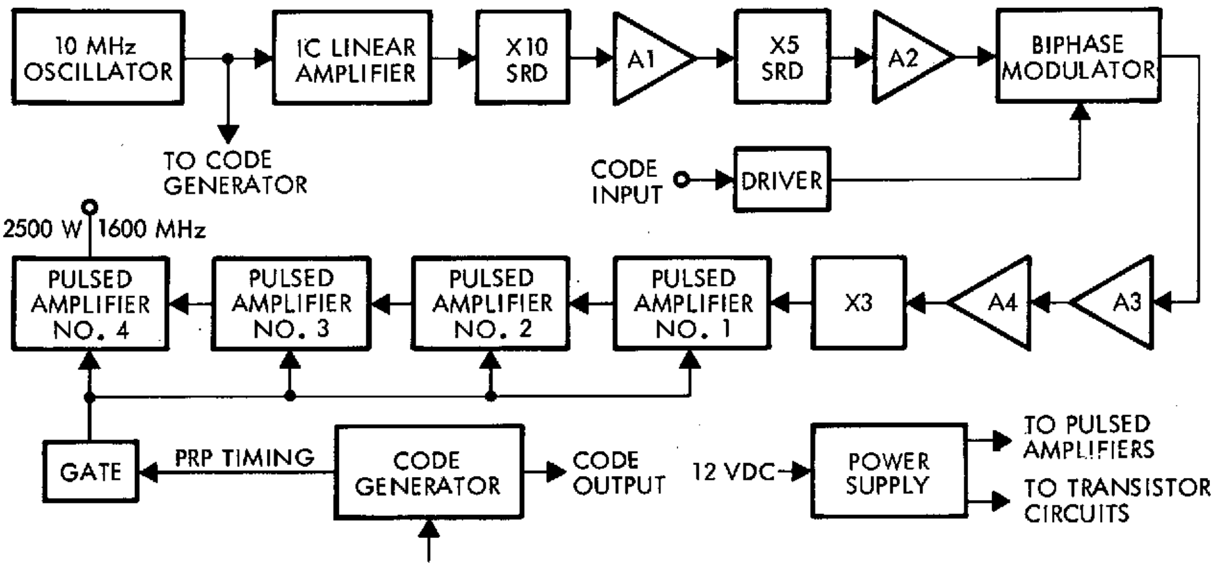


Figure 5. Transmitter Model A Block Diagram

Carrier Frequency

As listed in Table 5, three frequency bands for the aircraft-to-satellite links were examined for the surveillance system, 450, 900, and 1600 MHz. The 450-MHz band has the advantage of requiring the least transmitter peak output power. The upper two bands have the advantage of better propagation properties and smaller antenna dimensions, particularly on the satellite. However, antenna dimensions are not a problem at any of the frequencies.

The usual problem of spectrum availability and assignment plays the major role in the choice of frequency. At 1600 MHz, the largely unused frequency allocation for aeronautical radio services from 1535 to 1660 MHz is available; at 900 MHz, the top end of the UHF TV band or lower end of the TACAN band are possibilities; at 450 MHz, the DOD/FAA radar band is a possibility.

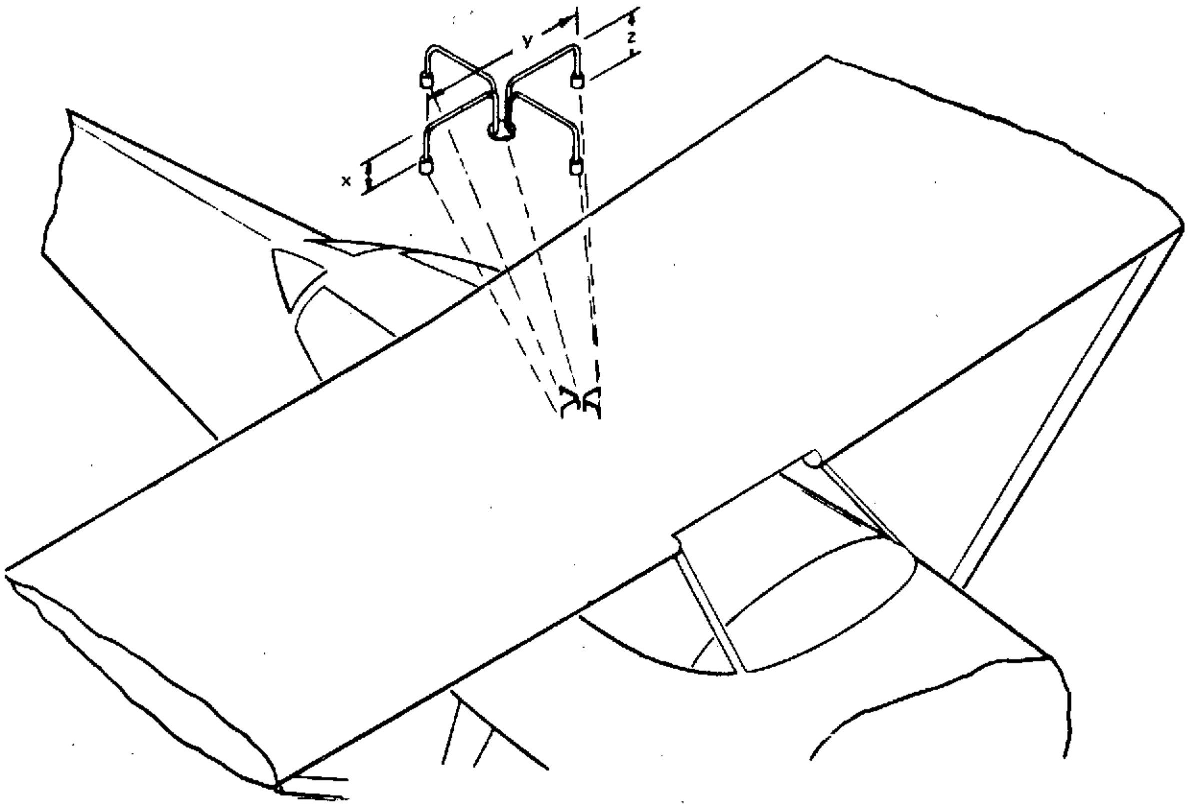
The satellite-to-ground links are at 5100 MHz, but can be placed in any convenient band above 2000 MHz. The main requirement here is that the propagation errors on the downlink do not degrade the overall accuracy and that the ground antennas have sufficient directivity so that the satellites can all transmit at the same frequency to conserve bandwidth.

Aircraft Antennas

Aircraft antennas suitable for general aviation have been experimentally studied to determine their coverage and gain capabilities assuming a Cessna 172 as representative of general aviation. The antenna configurations selected for experimental evaluation were the curved turnstile and curved dipole antennas. The antennas and ground plane were scaled for an operating frequency of 900 MHz. The results can be readily extrapolated to 450 MHz. Previous tests on antennas for the NAVSTAR system have already verified the requirements for a 1600 MHz operating frequency.

Pattern tests show that the desired coverage at all three bands can be provided by the turnstile antenna. The antenna is installed on the top of the wing or tail assembly. The antenna pattern coverage is near hemispherical with gains ranging from -3 to +4 dbi over a coverage cone of 160 degrees or better. Over the same coverage, the gain of the curved dipole antenna is approximately 3 db less than the curved turnstile. The degradation results primarily from losses resulting from the linear polarization of the curved dipole antenna. The turnstile antenna provides circular polarization, which is better matched to the circularly polarized satellite antennas.

The curved turnstile design can operate without a protective radome for low-speed aircraft. The antenna elements can be formed from metal rods whose ends are mounted directly to the aircraft surface through a fiberglass insulator. The design and mounting techniques are illustrated in Figure 6.



Frequency (MHz)	X (in.)	Y (in.)	Z (in.)
450	5.0	11.2	8.6
900	2.5	5.6	4.3
1600	1.7	4.8	2.5

Figure 6. Curved Turnstile Installation

Ground Multipath

In the location-identification system, ground multipath will induce delayed echoes similar in appearance to the direct signals from which they arise. If the receiver response to these echoes exceeds the detection threshold, false alarms will be generated. In principle, it is possible to reject each echo by predicting its time of occurrence; however, this prediction is an undesirable complication and may increase the pulse interference probabilities to undesirable levels. Consequently, we wish to look in detail at the echo characteristics to estimate the magnitude of the multipath problem at the receiver. Three factors enter this determination:

- Ground specular reflection coefficient
- Aircraft antenna directivity
- Time and frequency spread due to diffuse return.

It is estimated that the worst case multipath ratio (multipath/direct signal) is about -5.5 db and the average multipath ratio is about -17.5 db for aircraft antennas similar to the curved arm turnstile. Multipath could be decreased by 6 db or more if vertical polarization is used at the satellite antenna at low elevation angles. However, signal fading due to Faraday rotation in the ionosphere presents a problem. At 1600 MHz, maximum rotations of 20 or 25 degrees can be expected, which would not cause significant signal fading, but at 900 and 450 MHz rotations greater than 50 degrees can be expected, which are prohibitive. Therefore, with the possible exception of 1600-MHz operation, decreasing the multipath problem by vertical polarization of the satellite antenna is impractical.

It is clear that the interference due to multipath is less than the interference between direct signals since the multipath is usually well below the direct signal levels. However, depending on the distribution of multipath levels, the peak capacity of a channel may have to be reduced slightly from 50, 000 pulses/second.

The principal concern for multipath is false pulse saturation of the pulse computer. If all of the multipath returns coming into the computer are at the worst-case level they would constitute an intolerable load for the computer. This load can be avoided, however, by inhibiting sort initiation for any unidentified pulses from a particular satellite and code occurring within a selected time following any tracked pulse from that satellite and code. Exact inhibit period is not critical, but a value in the neighborhood of 40 microseconds appears reasonable.

3. ON-BOARD NAVIGATION

The NAVSTAR Concept

The same network of satellites used for surveillance will also radiate independent navigation signals. The navigation process is the reverse of the surveillance process in that, with the navigation system, the satellites radiate to aircraft (Figure 7) instead of aircraft radiating to the satellites. Similar position location principles apply, however, in both cases. (See Reference 9.) The navigation user measures the times of arrival of ranging signals from four satellites and computes his position in a manner similar to the surveillance computations of the ATC ground station. His task is much simpler, however, since he avoids the pulse sorting and identification of the surveillance system, and he computes only his own position. The navigation system provides the following features:

- Unsaturable, all-weather operation
- Common grid for all airspace
- Accurate position and altitude (50 to 300 feet) determined on the aircraft (area navigation)
- Accurate velocity and rate of climb information also available on the aircraft.

Each satellite in the constellation transmits signals in assigned time slots. The signals contain a ranging code plus digital data on satellite orbital parameters and oscillator error. The satellite transmissions are time division multiplexed so that an aircraft requires only a single-channel receiver which processes the data in sequence.

Oscillator time error data is required by the aircraft because the satellite transmissions are time-synchronized by individual, high-precision, crystal oscillators on each satellite. A ground tracking network determines the relative error among the satellite oscillators as part of the ephemeris calculations. This oscillator correction and satellite ephemeris data are transmitted periodically to the satellites, where they are stored and read out for transmission to aircraft.

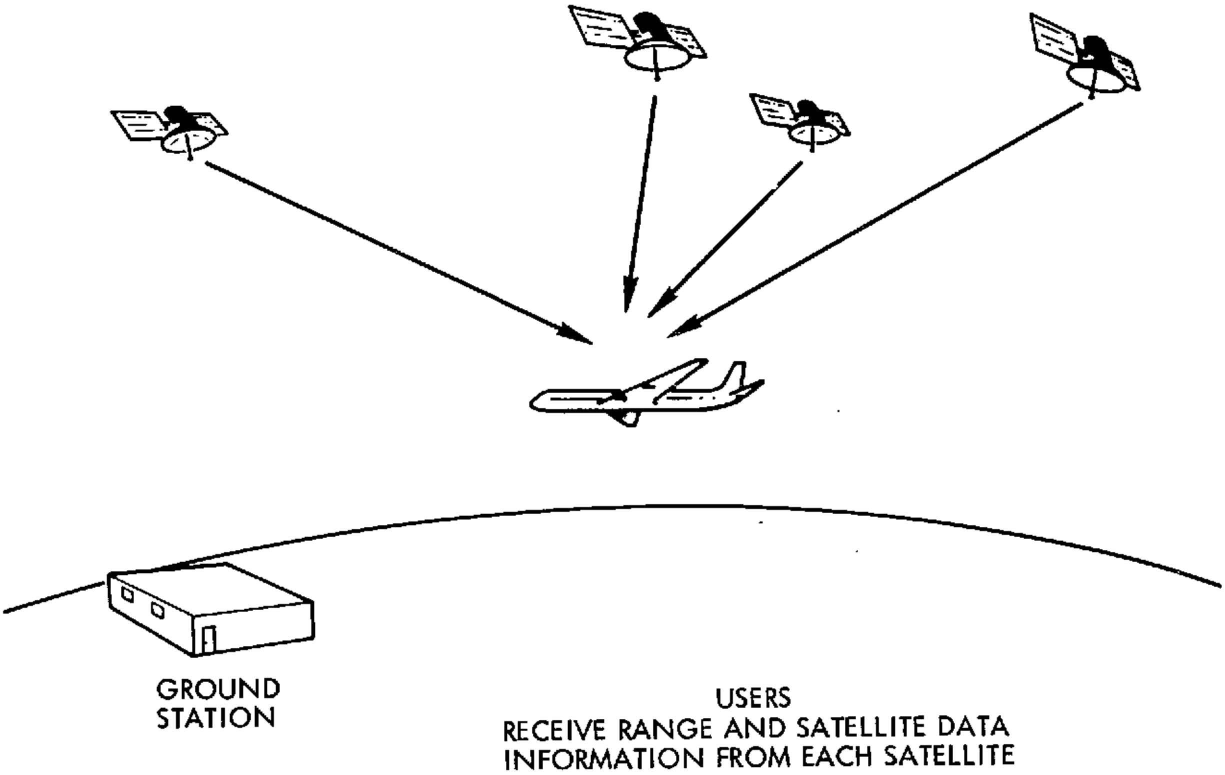


Figure 7. Satellite Navigation (NAVSTAR) System

Each satellite in the constellation transmits signals in assigned time slots. The signals contain a ranging code plus digital data on satellite orbital parameters and oscillator error. The satellite transmissions are time division multiplexed so that an aircraft requires only a single-channel receiver which processes the data in sequence.

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Avionics

The avionics required for the navigation user consists of a one-channel receiver and data processor, computer, and display. A single upper hemispherical coverage L-band antenna is required to receive the ranging signals. The elements of a typical system are illustrated in Figure 8 although the user hardware for receiving the ranging signals from the satellites and computing position can involve a wide range of costs and capabilities. Because of the cost of the avionics package, the system will not be a replacement for the VOR system. However, it should be competitive in cost and superior in performance to the VOR/DME area navigation systems now coming into use.

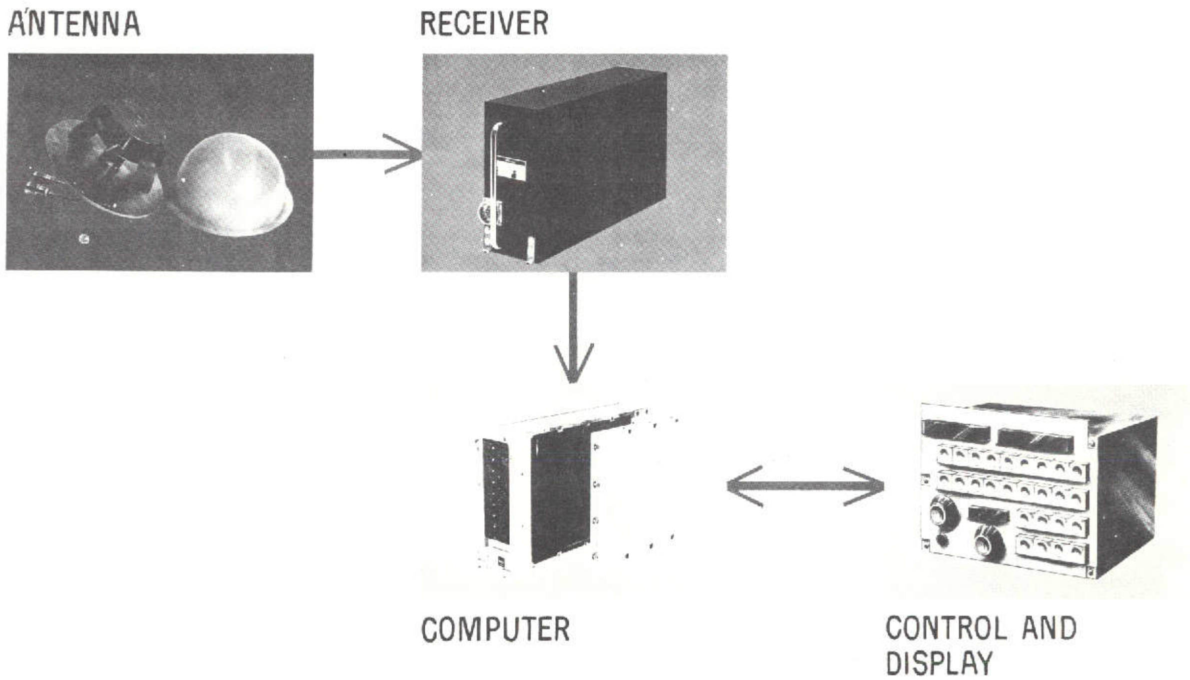

Figure 8. Navigation System Avionics

The output of the receiver is sent to a small digital computer for automatic computation of position. The display in Figure 8 is similar to that in a conventional inertial or doppler navigation system; however, the NAVSTAR equipment can drive any conventional or planned navigation display (e.g., moving map).

4. COMMUNICATION

Practically all air-ground communications for aircraft in the United States are conducted on VHF and UHF bands, the latter reserved primarily for governmental and military use. The frequencies of interest to air carriers and general aviation lie between 118 and 136 MHz. This band contains 360 channels (50 kHz spacing), with various segments allocated for particular uses such as airport towers, en route ATC, approach control, flight service stations, aeronautical enroute stations (air carrier), and the emergency frequency of 121.5 MHz. Navigation aids in the VHF and UHF region such as the VOR and ILS localizer facilities (108.1 to 117.9 MHz) also contain voice capability for ground-air communications.

Given the cost of satellite communications and the current investment in ground-based facilities, it is likely that the present air-ground VHF communications system or a modified form of it will continue for many years. The role of satellite communications, therefore, is to supplement the existing system.

Data rather than voice is the more promising technique for satellite-to-user links because it makes more efficient use of the link. Automatic data link techniques can significantly reduce pilot and controller workload. Two types of data links have been designed as illustrated in Figure 9. The larger is a two-way link at 1200 bits/sec each way for large aircraft (Ref. 9). Each satellite has capacity for two of these links.

LIT Backlink for Collision Warning

The high-priority LIT backlink is a rapid-access low-data-rate collision warning in which aircraft can be sent some 14 different messages for collision avoidance. This link works in conjunction with the location-identification surveillance in that the ground center utilizes knowledge of an aircraft's position and time of pulse transmissions to address that particular aircraft. The center transmits three RF pulses through three of the satellites. Reception of all three pulses in a window alerts the aircraft that it is being addressed by the ATC center. The window is then extended and the presence or absence of pulses in subsequent time slots establishes the message.

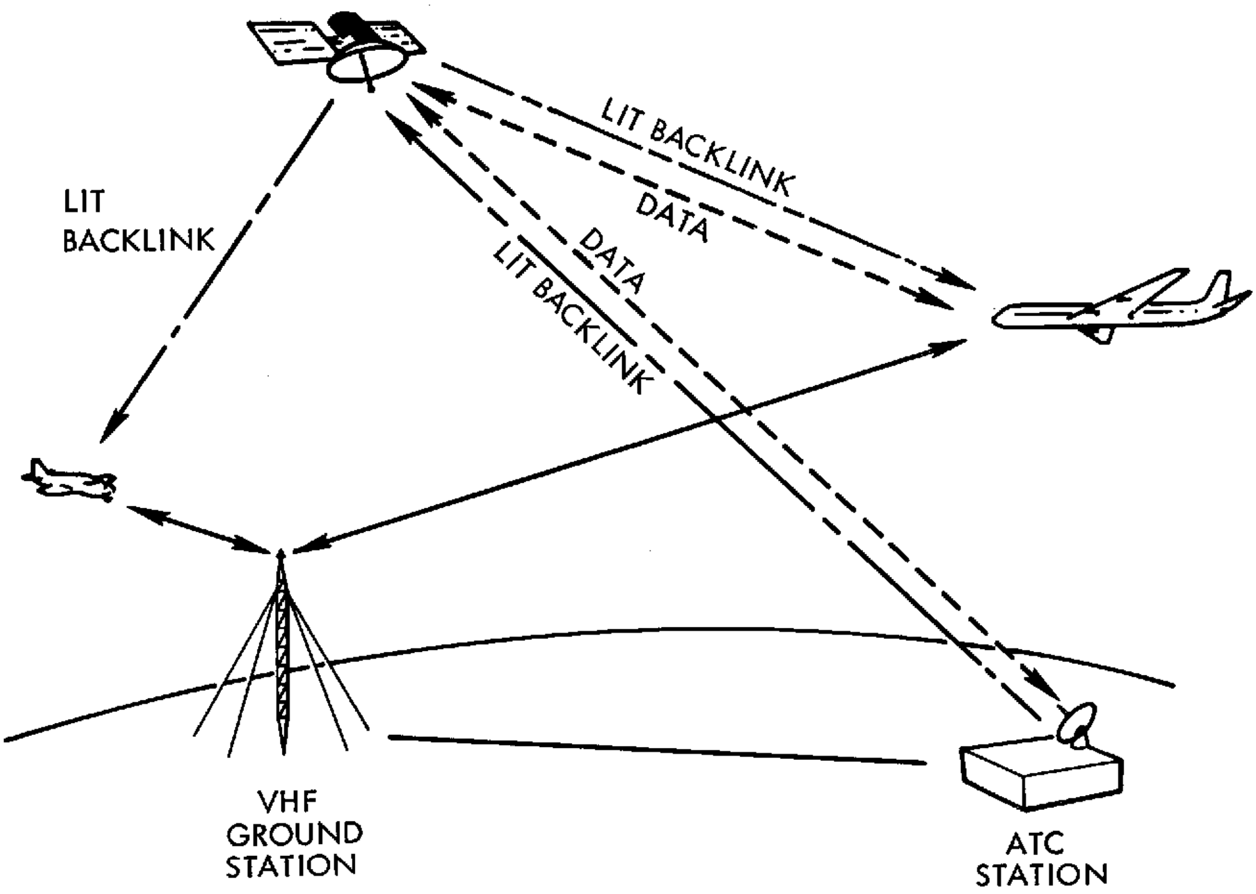

Figure 9. Satellite Communications Network

Figure 10 shows a 1560-MHz receiver which when added to the location-identification transmitter (LIT) provides the backlink function. The diagram is identical for the other two frequencies (receiver at 940 or 410 MHz) except for the local oscillator (LO) and possibly the intermediate frequency (IF). The LO source is obtained from the transmitter as are the timing pulses for the integrate and dump filter timing and sampling signals. The surveillance and backlink carriers are separated by 40 MHz so that the IF is centered at 40 MHz.

After each LIT pulse transmission, a control signal places a transmit/receive switch in the receive position. Since 50 milliseconds are allowed for the switching, the address window is opened by the message decoder for the next three 51-microsecond intervals after the pulse transmission. The window is extended another nine intervals if an address is received. At the end of this period, the switch is returned to the transmit position. The switch allows the same antenna to be used for both surveillance and the backlink, without a diplexer.

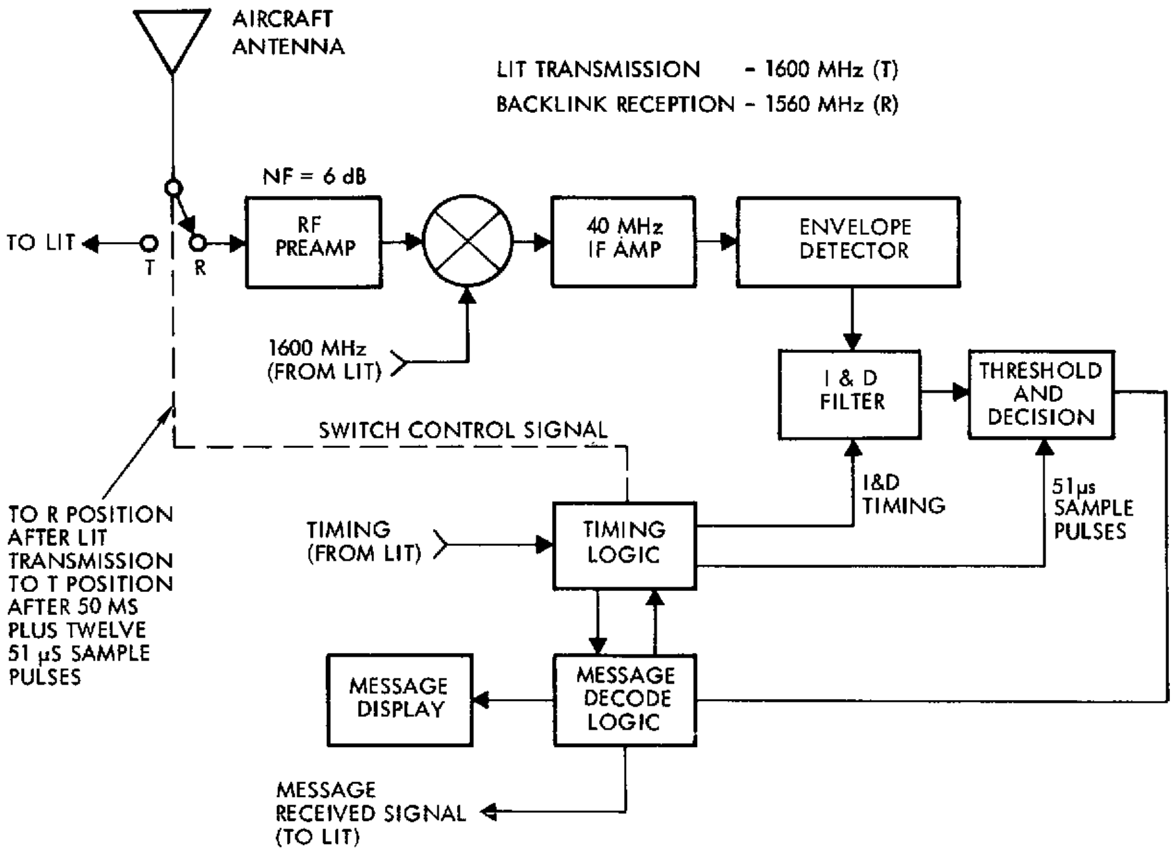

Figure 10. Backlink Receiver Block Diagram

The display indicates which one of 14 messages is received. A confirmation signal is sent to the transmitter telling it to delay its normal transmission time on the next LIT pulse by 10 microseconds to convey "message received" to the ATC center.

A single-error correcting, double-error detecting $\binom{8}{4}$ Hamming code is used for the messages. If the presence of a pulse indicates binary "one" and absence of a pulse binary "zero" then a message is simply the presence of four pulses in four of the eight message time slots. The transmission of message pulses is distributed equally among four satellites. This results in equal and minimum power requirements for each of the four satellites. A LIT backlink channel can transmit approximately 100 messages per second and occupies a bandwidth of about 200 kHz.

Data Link

Larger aircraft can use the additional capacity of the satellites for the transmission and reception of digital data. Each data channel will transmit at 1200 bits/sec in each direction. This transmission speed has been selected by the Radio Technical Commission for Aeronautics as the standard for aeronautical air-ground communications.

Some method of access by users to a data channel is required. Since an aircraft will not be able to hear other aircraft transmissions, the monitored approach in which aircraft use the channel when it is clear is not possible. A solution is to have the satellite transmit a low-power busy tone when it is receiving transmissions. Scheduled access in which aircraft transmit only at assigned times or controlled access in which aircraft transmit only upon receiving permission from the ATC centers are other possibilities.

5. DATA HANDLING

The system postulated here has a number of LIT data processing centers which calculate position data and send it to the air traffic control centers. To estimate the data processing load it is necessary to ascertain the impact of the LIT data on the ATC center and the data load for the LIT data processing center.

The ATC Centers

The total load for a post-1980's ATC system without LIT has been estimated by the ATCAC committee (Ref. 4). Results are summarized in Table 6 and include multiplying original estimates by a factor of 12 to account for the facts that a) some instructions are faster than others; b) there are "executive overhead" operations; and c) the program will be written in a higher order language. The resulting estimate for a terminal control center was 107.1 MIPS.

Table 6. ATCAC Computer Sizing Results

Function	En Route (MIPS)*	Terminal (MIPS)	National (MIPS)
Conflict prediction and resolution (mixed)	0.256		–
Conflict prediction and resolution (high density) (collision avoidance)	0.92	(in command and control)	–
Data acquisition	2.73	4.89	–
Command and control	0.56	1.46	–
Additional en route (displays, etc.)	2.92	–	–
Additional terminal	–	1.0	–
Central flow control	0.003	0.04	0.4
	7.39	8.92	0.4

*MIPS = Million instructions per second.

The LIT system does not alter the projections for collision avoidance, command and control, flow control, and "other" functions. These require aircraft position inputs and it does not matter significantly whether the data comes from beacon, radar, ground multilateration, or LIT. Since the data from LIT is very accurate in all three dimensions and updated quite frequently, the commanding rate may be slightly different and the collision avoidance function might have less to do, but the functions themselves certainly need not be complicated.

The main impact of the LIT system is on the data acquisition function. This function occupies a large part of the instruction load (37 percent for the en route problem and 55 percent for the terminal problem). In the system considered here, the position determination function is removed from the en route and terminal computers and moved to a set of LIT data processing centers since it would be very expensive to put a LIT receiver and data processor at every terminal and en route control center and would also result in considerable duplication of computation. Clearly one LIT data processing center (LDPC) can perform all of the LIT computations. Considering the consequences of the loss of the LDPC from some catastrophe such as fire or severe storm indicates that some redundancy is in order. Furthermore, the cost of point-to-point communications between LDPC's and ARTCC's can be reduced by some decentralization. In view of these considerations the decision was made to configure the ground system with four LDPC's.

For every airborne aircraft, a position message is sent from one of the LIT data processing centers to an ATC center about every second, the message consisting of identification, time, and position. Identification requires 18 bits, four for code and 14 for PRP. Time requires 16 bits, assuming that millisecond accuracy is required and that the time measurement is recycled every minute. The two horizontal position components, in rectangular coordinates relative to some point in the addressed ATC center, require 19 bits to provide resolution to 10 feet in a 500-mile square. The altitude components require 13 bits for 10-foot resolution. The total message is 85 bits. With 10^5 airborne aircraft the total communication load is 8.5×10^6 bits/sec.

The next question then is to determine how much of the computing load is thereby removed from the en route and terminal centers. The ATCAC report considered the following major functions for the data acquisition system (the values are for the terminal data processor):

- Scheduling of multilateration interrogations (1.4 MIPS)
- Multilateration tracking including position calculations (0.3 MIPS), and smoothing/prediction (2 MIPS)
- Correlation of search radar reports and multilateration predicted track positions (0.4 MIPS)
- Conversion to system coordinates (0.4 MIPS).

Miscellaneous calculations account for 0.4 MIPS to give a total of 4.9 MIPS for the data acquisition function for the terminal processor.

The LIT system would replace the beacon multilateration system assumed by the ATCAC report and the position determination function is now performed at the LDPC's. This leaves about 3.2 MIPS as the remaining computing load of the data acquisition system, i.e., the LIT data processing center will relieve each ATC center of about 20 percent of its computing load.

<u>The LIT Data Processing Center</u>

Each LIT data processing center is responsible for receiving data, decoding and unscrambling the data, and computing the position of all aircraft within its assigned region at some given rate, say once per aircraft per second. To prevent mid-air collisions near the borders of the assigned region it is necessary to add a buffer zone around the region and compute the position of aircraft within the buffer zone at the same rate as in the assigned zone. Outside of the buffer zone, i.e., for the rest of the country, aircraft positions can be calculated less frequently, i.e., about every two minutes.

The LDPC computer program has four major blocks. One program compares the observed pulse times with predicted pulse times for all the aircraft with known PRP's and codes. This program outputs the identified pulses to the position calculation program, which computes aircraft position from the pulse times and sends these positions to the appropriate air traffic control centers. All unidentified pulses are sent to the position calculation program. Any pulses still not identified are sent to the executive program, which collects and displays statistics on unidentified pulses. The comparison program also sends data on missing pulses to the executive program.

In the steady-state operation of the system, the largest data processing task is the computation of position data. With a straightforward algorithm for computing position data, approximately 1000 computer instructions suffice to calculate a position. If the LDPC is responsible for computing 25,000 aircraft positions every second, the computing load is 25 MIPS.

A more serious problem appears when the computer program is starting and must identify all of the aircraft from their PRP's. This might occur after a computer failure in which the computer memory has been erased. Sorting all of the 100,000 aircraft might take as much as fourteen minutes on the postulated computer system. Future advances may reduce the problem significantly; optical data processing, for example, may provide a feasible and fast method for sorting out the PRP's.

The computation for the LIT data processing center can be divided into parallel tasks. The position determination calculations are independent and can be carried out simultaneously for many aircraft. The sorting problem also involves many calculations which can be done simultaneously. This kind of problem, a large computing load in which most of the computations can be done in parallel, suggests the use of minicomputers (Referenc 11) which are becoming increasingly popular for this type of problem. Typically, a minicomputer with a 1-MIPS speed and 4000 words of core storage costs around $10,000.

A large computer is still needed for executive and scheduling functions, to maintain satellite positions and to send the satellite positions to the minicomputer storage.

The raw pulse data for one code would be sent to a minicomputer, which compares the predicted and observed pulses for that code only. With 100,000 pulses per second arriving, each of the 16 minicomputers is required to handle an average of about 6000 pulses per second. With 50 instructions per pulse, a minicomputer is required to perform 300,000 instructions per second, which is well within the capacity of existing computers. If two seconds of data (measured and predicted pulses) are stored by the minicomputer, an average of 24, 000 words of storage is required by each of the minicomputers.

A minicomputer is assigned the task of sorting the pulses for a single code. The computing load for each code is about 9 N^2/C, where N is the number of unidentified pulses for this code. In the steady-state this load is very light. If the number of unidentified pulses for a single code reaches 2000 per second, five seconds of data are collected before being processed; the computing load is then about 1 MIPS, still within the capacity of a minicomputer. If the number of unidentified pulses gets larger, the system would enter a special mode of operation to concentrate on the sorting task.

The position determination program for a single code could be assigned to a set of two minicomputers. A single minicomputer is then required to handle an average of about 1000 aircraft per second. With 1000 instructions per aircraft, each minicomputer is required to perform 1 MIPS. If the number of unidentified aircraft gets too large for the sorter program to handle, the minicomputer assigned to position determination would be reassigned to sorting.

The executive operations for a particular code would also be assigned to a minicomputer. With 200 instructions per aircraft, the computing load on each of these minicomputers is about 1 MIPS.

6. AVAILABILITY AND COST

The design tradeoffs involving the satellite network are the availability, quality of service, and cost in providing the three principal services of communication, navigation, and surveillance. As indicated in other studies (References 9, 10, 12, 13, and 14) there are a number of useful satellite constellations to choose from.

Reliability and Availability

A satellite with a 12.5-year MTBF and a seven-year design life (current state of the art) provides high system availability for a six-satellite configuration. Outage* during a 30-year projected system life span is less than two percent. The probability of outage for a system operational life of 99 years is still less than five percent. The expected outage time would be about two or three weeks. For such a system, a maintenance launch rate of approximately 1.2 launches per year is required.

To provide a data link service, each satellite could accept an additional payload of three or four 1200 bits/sec data transponders. For the recommended system, the four satellites in inclined orbits are postulated to have two such channels. The MTBF for the satellites with data channels is reduced from 12.5 to 9.8 years, with the design life remaining at seven years. The resulting satellite system has a probability of system outage for a 30-year life span of about 3.5 percent. For such a system, a launch rate is still approximately 1.2 launches per year.

Coverage

While a satellite constellation of synchronous equatorial satellites keeps a fixed geometry at any point on the earth, thereby simplifying user search and acquisition, the geometry to users in the United States does not yield acceptable accuracy. The constellation which has been

*Outage is defined as having less than four operational satellites available. Since it is possible to determine aircraft position when two or three satellites are available, the probability of outage is conservatively defined.

studied extensively places two satellites in equatorial synchronous orbit and four others with inclined elliptical orbits with their ground tracks circling a central point. It is termed a "rotating X" configuration.

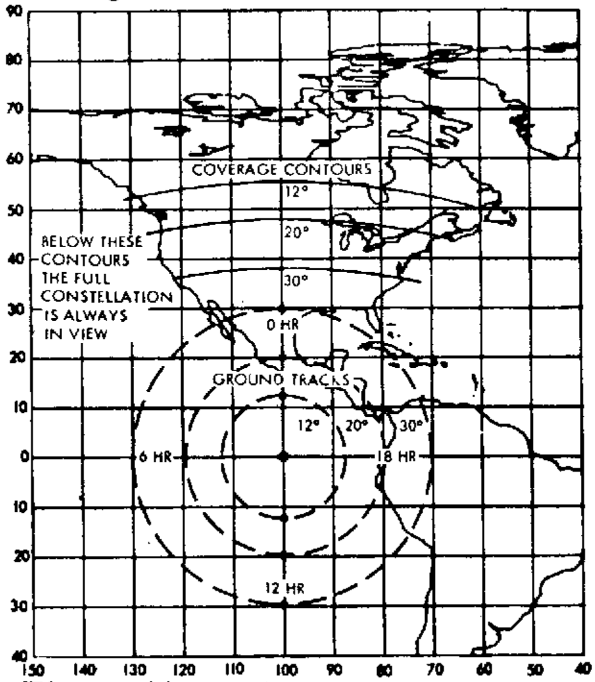

Figure 11. Orbit Ground Tracks and Coverage Contours

Figure 11 shows approximate ground tracks and coverage contours for different rotating X configurations. It can be seen that 30-degree inclinations are not suitable for full-time full-view coverage of the United States by all satellites; something less than 20 degrees is required. A 12-degree orbit on the other hand takes in much of southern Canada, but at the cost of some accuracy. The recommended inclination is thus 16 degrees.

Avionics Costs

With regard to communications, the SATCOM usage which has received considerable attention is related to the over-ocean application (see, for example, References 9, 15, and 16). The resulting price of the onboard equipment is on the order of $10,000. Although this cost precludes most general aviation users, it may well be a reasonable investment for commercial transports and many military users. With regard to navigation, Table 7 summarizes the projected cost and weight of the navigation hardware for three out of many possible classes of users. Although in all cases these costs are low for the service provided, it is clear that many of the general aviation user will not be able to afford this service. The cost is that projected for antennas, receivers, computer, and displays.

Table 7. Navigation User Hardware Characteristics

	Weight (lb)	Cost ($)
Low cost	15	5,000
Moderate cost	15	9,600
High performance	40	25,000

With respect to surveillance, the results of the TRW costing estimate are shown in Table 8. In addition manufacturers of general aviation equipment were invited to participate in estimating the probable cost of the location-identification transmitter. The results are presented in Table 9. Differences in quality levels and accessories between the various manufacturers and models as well as variations in manufacturing and marketing practices among the companies explain the variance in estimates. Moreover, no effort was possible in the vendor engineering-pricing efforts to identify and explore ways to reduce the cost of the LIT transmitter.

Table 8. TRW Location-Identification Transmitter Price Estimates

Current Material Costs in Dollars for Production Quantities of 1,000 to 10,000

	Manufacturing Unit Cost			FOB Price		
Quantity	1,000	2,500	10,000	1,000	2,500	10,000
Design A	810	743	659	972	892	791
Design C	623	575	459	748	690	551
Design D	445	419	362	534	503	434

	List Price			Discount Price		
Quantity	1,000	2,500	10,000	1,000	2,500	10,000
Design A	1,944	1,784	1,582	1,555	1,427	1,266
Design C	1,496	1,380	1,100	1,197	1,100	882
Design D	1,068	1,006	868	854	805	694

Note: Designs A, C, D defined in Table 5.

All estimates are based on current designs and production techniques. However, the price in 1980, when the majority of the aircraft are being equipped, is of more interest. Analysis of the transmitter to determine the price changes in relative 1971 dollars by 1980 indicates that a decrease in material costs is likely. Although components for the design and production of LIT are available today, new components may evolve which will significantly reduce the complexity of the existing design.

Table 9. Vendor Quotations for Location-Identification Transmitter

(Design C)

Vendor	10,000 Unit Quotation ($)	Radar Transponder Price ($)*
King	1380	1195, 2150
Wilcox	1800	2250, 4359
Narco	1800	1295, 1975
Collins	2000	5606
Bendix	2750	1212, 2511, 4632
Genave	--	795
TRW	1100	--
Average list price	1800	2542**

*From Reference 17. Production quantities not given, but assumed to be between 2000 and 4000.

**For 10,000-unit production average transponder price is estimated to be $1960.

In the location-identification transmitter the high-cost items are primarily those which operate at high power levels (diodes, transistors, and tubes) and the large-scale integrated circuits. Technology development programs, both Government and privately-sponsored, are dedicated to increasing the capability of devices for increased power and complexity. Figure 12 demonstrates the advances made to date. If present trends are projected to 1980, the results will be:

- A wider selection of devices
- A reduction in total parts count
- A reduction in parts cost.

TRW also investigated the price change for integrated circuits during the past 10 years. During these years, the technology was maturing. When mature, the cost change with time is small. Those parts from a mature technology were eliminated from any price projection. Immature parts were projected downward in cost. Factoring the costs on this basis resulted in the comparison shown in Table 10. Thus, assuming these cost reductions, by 1980 a Type C LIT is expected to sell for about $838 list and $683 discount. Furthermore, a 1980 Type D LIT transmitter would be expected to sell for about $656 list and $525 discount.

TRANSISTOR TYPE	YEAR	POWER
SAIL	1960	30 - 100mw
2N3959	1966	0.4
2N4431	1967	5
↓	↓	5
	1970	10

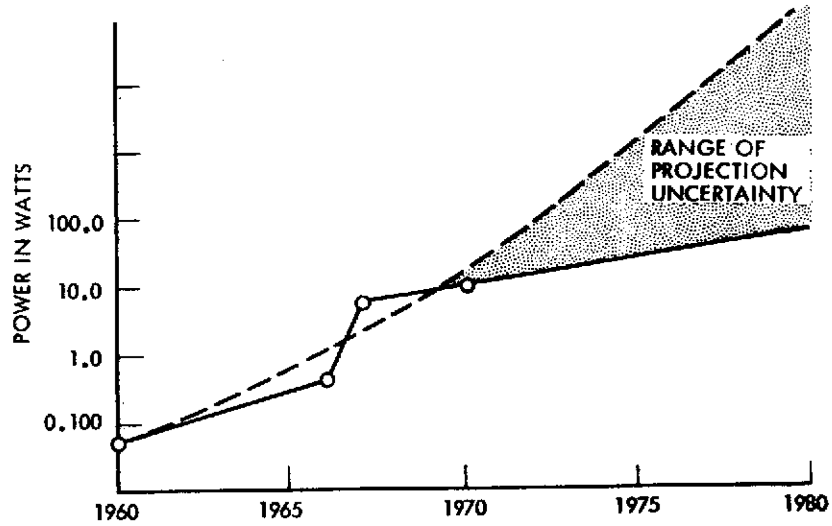

Figure 12. History and Projection for Transistor Power Level

Satellite Costs

The satellites will represent a significant cost for the FAA and therefore should be compared in cost with competing techniques. The satellite costing effort on this study, although brief, is based on substantial recent and relevant satellite design and test program experience. Table 11 summarizes the costs involved in placing a satellite as described in Section 1 into orbit. Launch vehicle, launch costs, and range costs (Ref. 18) are representative of those associated with the Delta 904 except that the $2.4 million launch costs represents an increase by a factor of over 1.5, to account for the fact that the satellite system, since it will launch a spacecraft approximately every 10 months, will have a somewhat lower launch rate than, say, a scientific or communications satellite program that might launch three or four spacecraft at four-month intervals and then stop. The program management cost is based on recent military and civilian programs in which program management costs by the Government agency typically run approximately 8 percent of total program costs. A launch rate of 1.2 launches per year accounts for the $18 million per year figure.

Table 10. LIT Price Projections, in Dollars

Type A (1000 Units)	1970	1980 (Tubes)	1980 (Transistors)
Material	690	609	580
Labor	120	120	120
Manufacturing cost	810	729	700
FOB price (120%)(3)	972	875	840
Retail price (x2) (4)	1,944	1,750	1,680
Discount price (80 of price) (5)	1,555	1,400	1,344
Type A (2500 Units)			
Material	633	552	523
Labor	110	110	110
Manufacturing cost	743	662	663
FOB price	892	794	760
Retail price	1,784	1,588	1,520
Discount price	1,427	1,270	1,216
Type A (10,000 Units)			
Material	560	479	450
Labor	99	99	99
Manufacturing cost	659	578	549
FOB price	791	694	659
Retail price	1,582	1,388	1,318
Discount price	1,266	1,110	1,054
Type C (1000)			
Material	504	423	394
Labor	119	119	119
Manufacturing cost	623	542	513
FOB price	748	650	616
Retail price	1,496	1,300	1,232
Discount price	1,197	1,040	986
Type C (2500)			
Material	465	384	355
Labor	110	110	110
Manufacturing cost	575	494	465
FOB price	690	595	560
Retail price	1,380	1,190	1,120
Discount price	1,100	950	890
Type C (10,000)%			
Material	360	280	251
Labor	98	98	98
Manufacturing cost	495	378	349
FOB price	551	454	419
Retail price	1,100	908	838
Discount price	882	726	670
Type D (1000)			
Material	326	259	237
Labor	119	119	119
Manufacturing cost	445	378	356
FOB price	534	454	427
Retail price	1,068	908	854
Discount	854	726	683
Type D (2500)			
Material	310	243	221
Labor	109	109	109
Manufacturing cost	419	352	330
FOB price	503	422	396
Retail price	1,006	844	792
Discount price	805	675	634
Type D (10,000)			
Materialp	264	197	175
Labor	98	98	98
Manufacturing cost	362	295	273
FOB price	434	354	328
Retail price	868	708	656
Discount	694	566	525

Table 11. Satellite System Cost Estimates

Spacecraft	\$ 7.0 million
Launch vehicle	3.0
Launch	2.4
Range	0.6
Program management (government)	1.0
Contingency	1.0
Total:	\$15.0 million per launch
Average:	\$18.0 million per year

Table 12 estimates satellite development and acquisition cost. The \$110 million is based on recent experience at TRW on similar programs. The acquisition figure of \$45 million represents the launching of three additional satellites at the conclusion of the development and demonstration program. Since five satellites would be launched during that program, it is assumed that at least three should remain operational at the time of the desired initial operational capability. The additional three satellites (to bring the constellation up to the recommended six satellites) at a \$15 million in-orbit cost account for the \$45 million, bringing the total development and acquisition cost to \$155 million.

Table 12. Satellite Development and Acquisition Cost Estimates

Development (five satellite program)	
Contractor	\$ 70 million
Government	10
Test/demonstration (five launches)	30
	\$110 million
Acquisition	
~3 additional satellites	~\$ 45 million
Development and acquisition	\$155 million

Ground System Costs

The estimated costs of the ground system given in Table 13 cover the initial cost of four LIT data processing centers, one command and control station, the ground communications network, the LIT calibration beacon network, operation and maintenance of those facilities for the first year, and associated software development. Cost of the 20 Air Route Traffic Control Centers is not included.

Table 13. Ground System Cost Summary

System Element				Total ($000)
Program Acquisition				9,365
LIT Data Processing Centers (four sites)				59,000
Facilities		850		
Equipment		9,752	Initial cost per site through 1 year O&M	
Software		2,500		
O&M		1,648		
	Total	14,750		
Command and Control Station				6,280
Facilities		327		
Equipment		4,695	Initial cost through 1 year O&M	
Software		800		
O&M		458		
	Total	6,280		
Ground Communications Network (first year)				15,925
LIT Calibration Beacon Network (50 sites)				750
Total Initial Cost Through First Year O&M				91,320
Annual Operating Cost After First Year				25,055

Cost Comparisons

The essential ATC function which the satellite system is recommended to replace is that of radar surveillance. The FAA investment in the ground element of the present radar surveillance system including both the en route and terminal area primary and secondary radars, and associated remote equipment, represents about $330 million and, with the continued installation of new radar, is projected to grow to over $750 million by 1980. The projection does not include advanced features such as discrete addressing as proposed by the ATCAC and approved by the FAA. No cost figures are available for the advanced radar concept recommended by the ATCAC. The average annual expenditure in the 1980 time frame for radar surveillance is approximately $42 million for operations and maintenance and $73 million for facilities and equipment, for a total of about $115 million. (References 1, 19, 20, and 21).

Table 14 shows the costs for satellite and radar-based ATC system approaches. Although this comparison is necessarily based on the limited data available, both sides of the table are considered accurate and representative. Thus one can infer that the satellite system is clearly cost competitive with a radar system providing less service.

Table 14. Satellite-Based Versus Radar-Based ATC System Comparisons

	Satellite System		Present Radar System*	
Major Services	Surveillance, Collision Warning, Navigation ($M)		Primary Plus Secondary Radar ($M)	
R&D and acquisition	Satellites	155	Radar/ground stations	750
	Ground stations	91		
		246		
Annual cost	Satellites	18	Operations and maintenance	42
	Ground stations	25	Facilities and equipment	73
		43		115
Total cost through finish	R&D and acquisition	246	10-year operational	1150
			R&D/acquisition	750
	10-year operational	430	Total	1900
		676		

*Future air traffic control system cost radar elements were not estimated on this study; advanced radar system costs will probably be much greater than those shown here.

The following conclusions can be drawn from the foregoing analyses:

- The location-identification transmitter can be marketed for less than the ATC transponder, especially when that transponder is modified to include altitude encoding. The ultimate price will probably be in the range from \$500 to \$1000.

- The price of either the location-identification transmitter or the ATC radar transponder will probably eventually be low enough so that mandatory use of such equipment for the vast majority of aircraft flying in anything but remote areas will be acceptable to the aviation public.

- The costs associated with maintaining a six-satellite constellation providing surveillance, short access time collision warning, a navigation service, and limited communications can be achieved for substantially below the figure required for radar alone.

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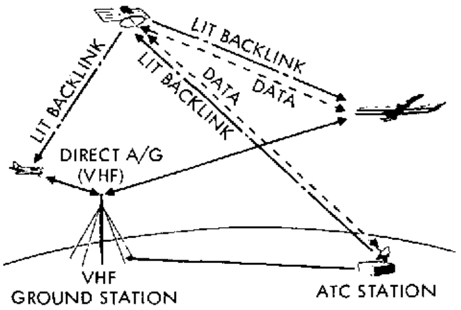
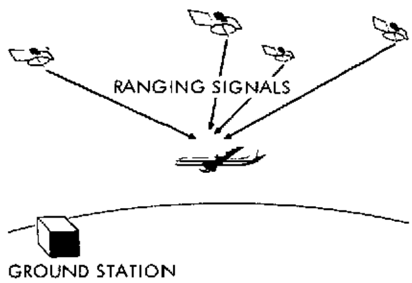
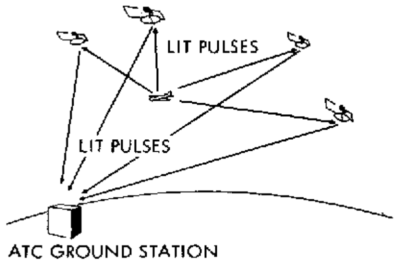
COMMUNICATIONS	NAVIGATION	SURVEILLANCE
		

PARAMETER	DATA	LIT BACKLINK
CHANNELS	2/SAT.	2
CAPACITY/CH	1200 BPS FULL DUPLEX	100 MESSAGES/ SEC
CARRIER FREQ	5140-5170 MHz(Gnd) 950-980 MHz(A/C)	5050 MHz UP 940 MHz DOWN
BANDWIDTH	100 KHz/SAT	500 KHz

PARAMETER	NAVSTAR
CHANNELS	1
CAPACITY	UNLIMITED
CARRIER FREQ	1550 MHz
BANDWIDTH	2 MHz

PARAMETER	LIT
CHANNELS	2
CAPACITY/CH	50,000 UPDATES/ SEC
CARRIER FREQ	912.5 MHz UP 5087.5 MHz DOWN
BANDWIDTH	50 MHz

NOTE: SAME SATELLITES FOR ALL THREE FUNCTIONS. CARRIER FREQUENCIES ARE TENTATIVE AND APPROXIMATE.

SYSTEM DATA

6-SATELLITE 16° X-CONFIGURATION

~200 FT ACCURACY (1σ ALT, HORIZONTAL CEP)

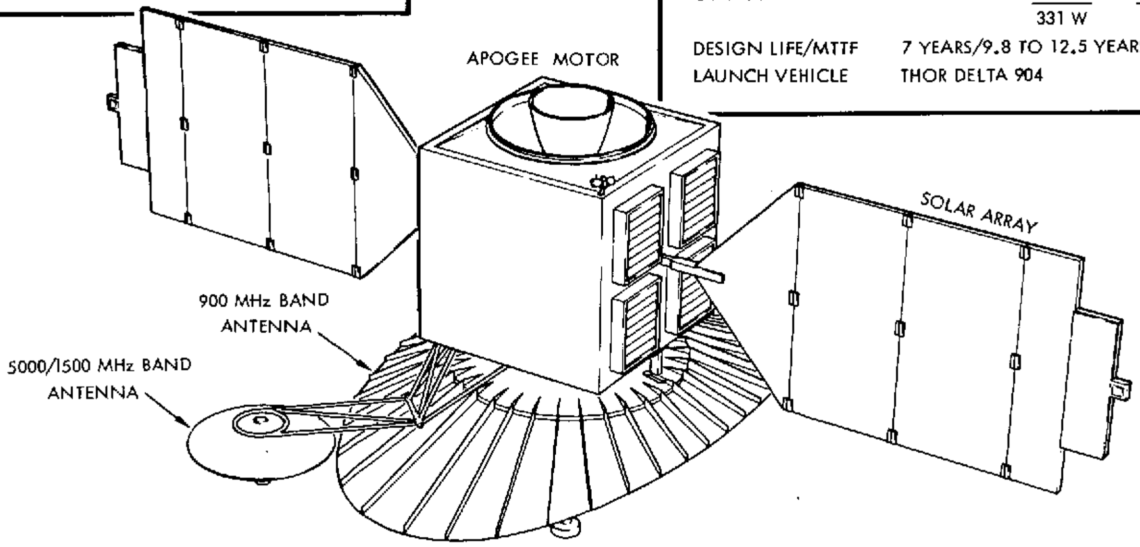
PROBABILITY OF OUTAGE, 30 YR LIFE ≅ 3.3%

SATELLITE DATA

PAYLOAD	2 LIT	100 W	20 LB
	2 LIT BACKLINK	46 W	20 LB
	1 NAVSTAR	25 W	25 LB
	2 DATA LINK	60 W	20 LB
OTHER SATELLITE FUNCTIONS		100 W	637 (1146) LB
		331 W	722 (1231) LB

DESIGN LIFE/MTTF 7 YEARS/9.8 TO 12.5 YEARS

LAUNCH VEHICLE THOR DELTA 904



LIT SYSTEM CAPACITY

ATCAC AIRCRAFT POPULATION FORECAST
1995 - 54,000 PEAK AIRBORNE
525,000 REGISTERED

LIT CHANNEL CAPACITY (25 MHz BAND)
50,000 AIRCRAFT POSITION UPDATES/SEC
500,000 AIRCRAFT ID'S ASSIGNABLE *

* FROM PRODUCT OF 31,255 PRP'S AND 16 BIPHASE CODES

LIT MODULATION PARAMETERS

TRANSMITTED PULSE WIDTH	51.1 μSEC
PULSE REPETITION PERIOD (PRP)	BETWEEN 1.0 AND 1.31 SEC/PULSE
NUMBER OF DISCRETE PRP'S	31,255 - SPACED 10 μSEC APART
BIPHASE CODE LENGTH	511 BITS
BIT LENGTH	0.1 μSEC (COMPRESSED PULSE WIDTH)
NUMBER OF BIPHASE CODES	16